14: Original Spin

Physics 17: Black Holes and Extreme Astrophysics

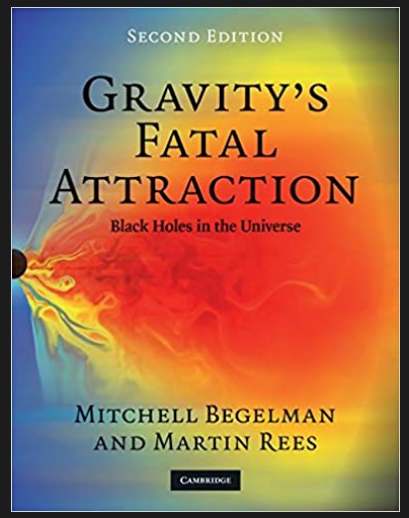
Reprise

- Angular momentum ($J = mrv$) of a rotating object must be conserved (L3.9)
- As gas collapses under gravity, conservation of angular momentum amplifies rotation (L7.13)
- Rotating gas spirals into a black hole through a flattened accretion disk (L7.14)
- Matter makes spacetime curve, and we experience spacetime curvature as gravity (L12.21)
- Extreme curvature of spacetime around a compact object produces a black hole with an event horizon (L13)

Goals

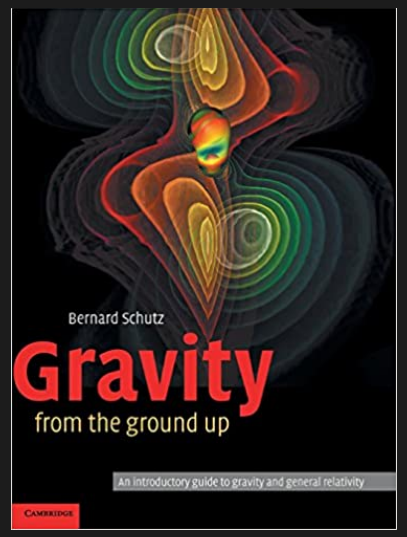
- Describe spinning black holes
- Discover how we can measure the spin of astrophysical black holes
- Discuss the importance of black hole spin

Reading



Begelman & Rees

- X-ray observations (p225-228)
- Spinning black holes (p232)



Schutz

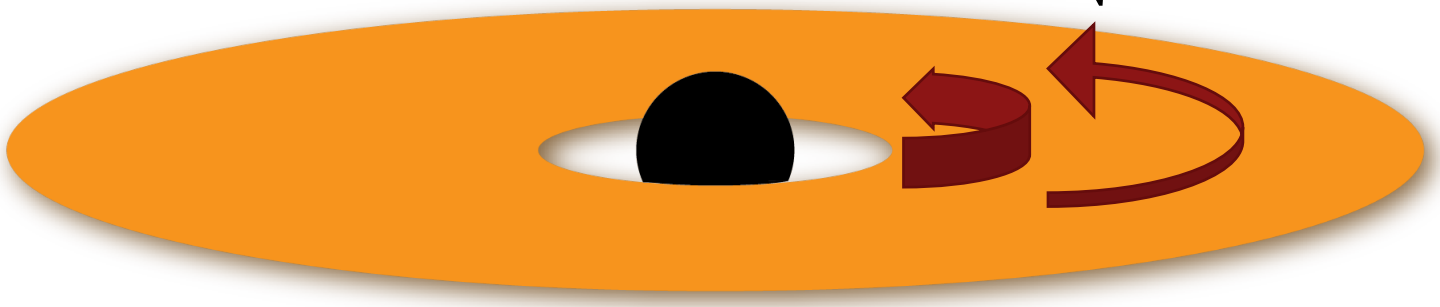
- Spinning black holes (p296-299)
- X-ray observations (p300-302)

You can access Schutz online via library.stanford.edu

The Accretion Disk

Material at smaller radii is orbiting faster than material at larger radii

$$v = \sqrt{\frac{GM}{r}}$$



Friction transfers angular momentum outward

Temperature of gas increases towards center

Emits radiation like a black body, but at 10 million deg, so emits X-rays as well as UV & visible light

As gas loses angular momentum, it falls inward

At each radius in the disk, gas is on a stable, circular orbit around the black hole

Material at smaller radii orbits faster than material at larger radii (Kepler's law)

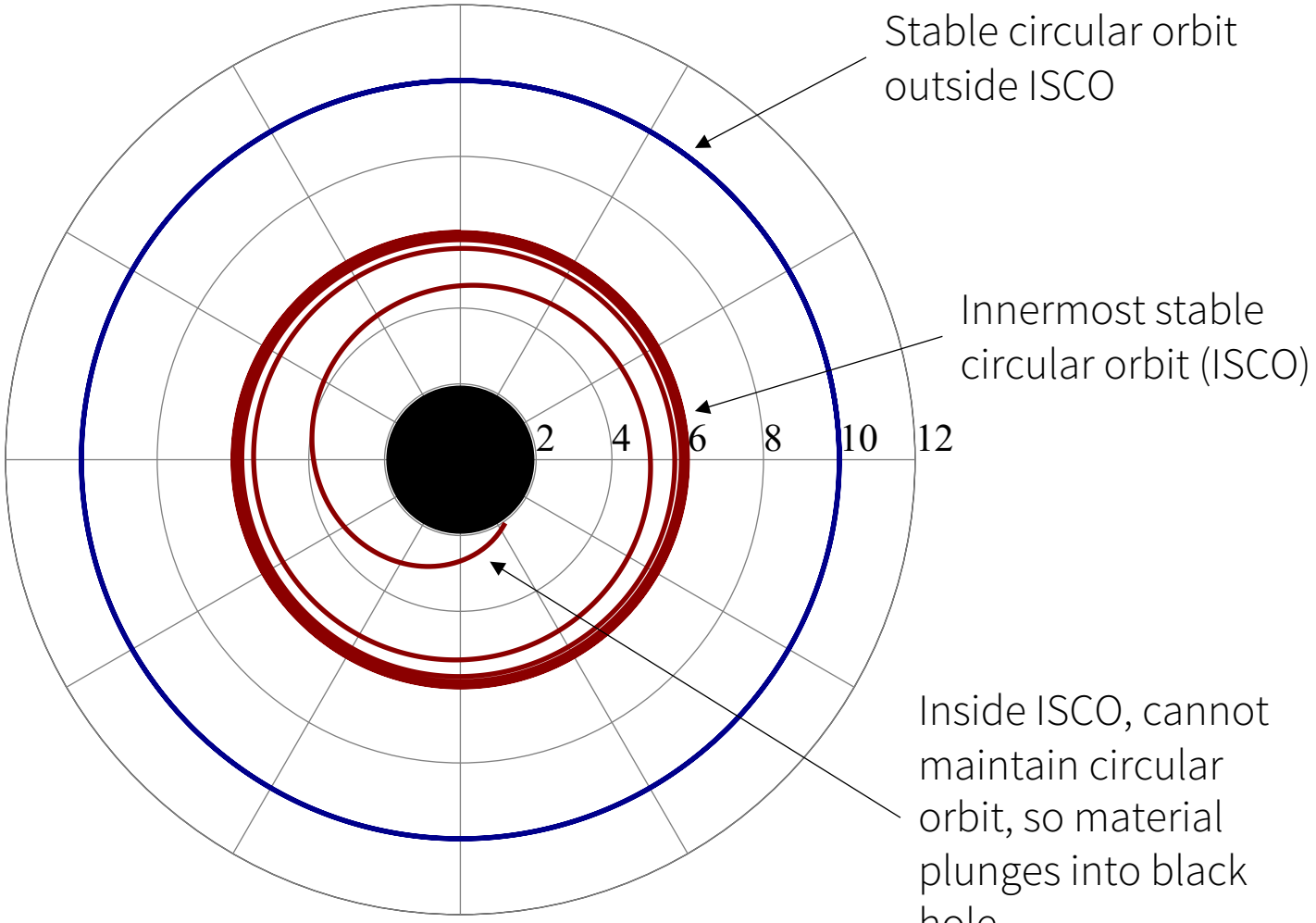
There is friction between the fast-moving inner gas drags the slow-moving gas near it and speeds it up

- Angular momentum is passed outwards
- As gas loses its angular momentum, it falls inwards
- Normal 'viscous' friction is not strong enough
- Friction is generated by magnetic fields that are pulled round by plasma in the disk

Gas gradually spirals in, towards the black hole, through the disk

WILtY L7.16

The Stability of Orbits



In Newtonian gravity, a stable orbit is possible at any radius

- A stable orbit is an orbit which, if perturbed slightly, will return to its original state

In General Relativity, a stable orbit is only possible outside the innermost stable circular orbit (ISCO)

$$r_{\mathrm{ISCO}} = 6\,{}^{GM}/_{c^2}$$

(for a non-spinning black hole)

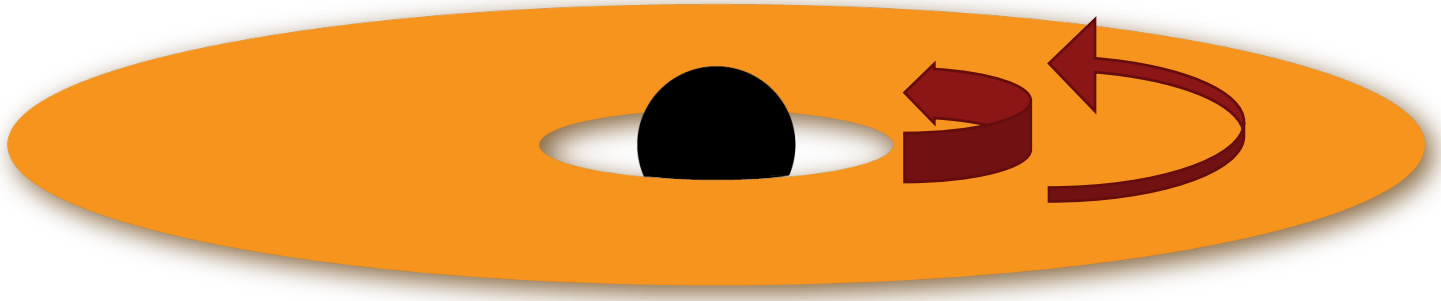
Within the ISCO, strong gravity (due to extreme spacetime curvature) prevents a stable orbit. Material inside the ISCO plunges rapidly into the black hole

Bigl

Orbits in the Accretion Disk

Innermost stable circular orbit $r_{\mathrm{ISCO}} = 6\,{}^{GM}/_{c^2}$ (for a non-spinning black hole)

Gas outside the ISCO maintains stable circular orbits and spirals slowly inwards



Gas inside the ISCO plunges rapidly into the black hole

What happens to the angular momentum of the gas plunging into the black hole?

It must be conserved. The black hole gains angular momentum and spins up

Gas only remains on stable circular orbits outside the innermost stable circular orbit (ISCO)

Gas on stable orbits gradually spirals inwards as it loses angular momentum by friction

- Moves radially inward more slowly than it moves in orbit

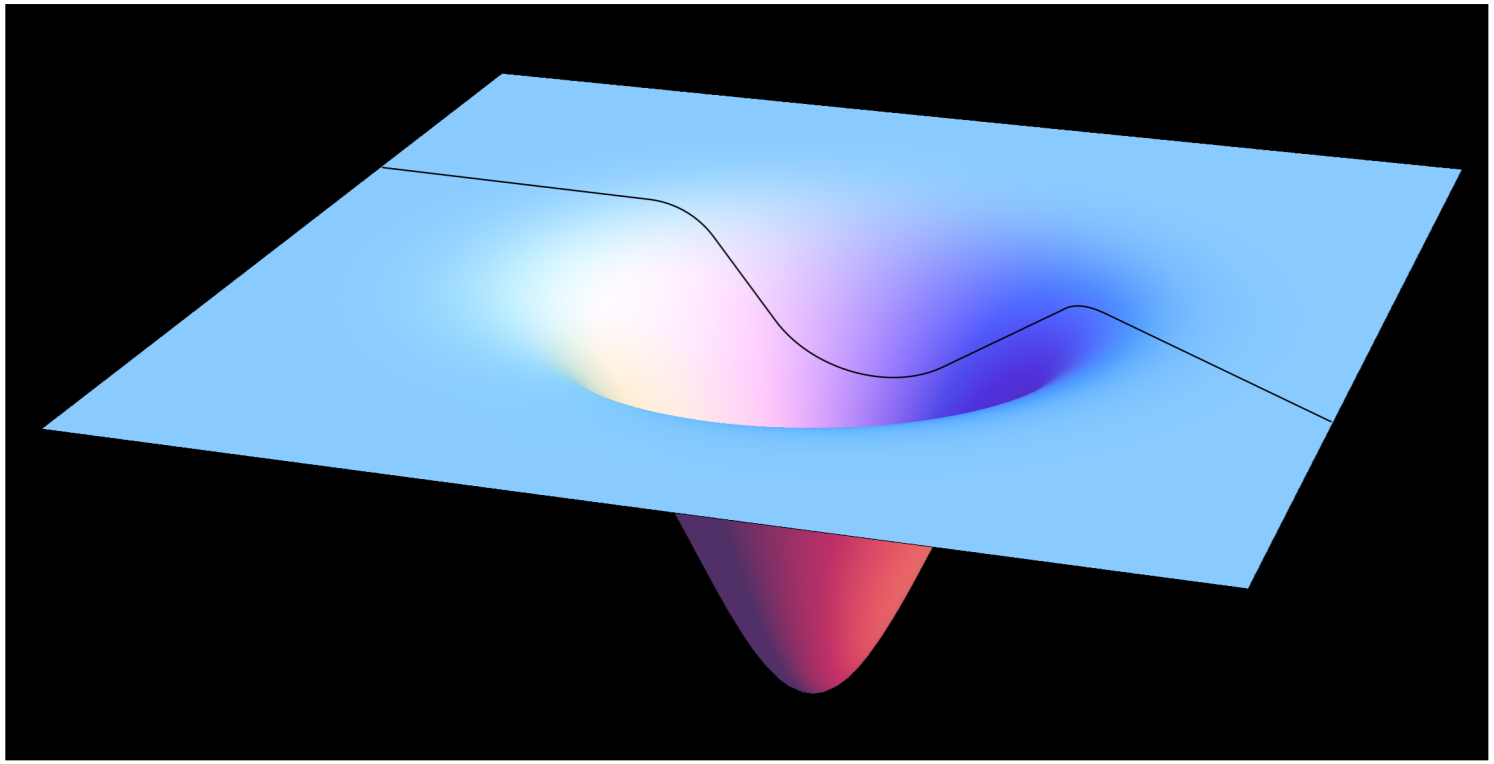
Once gas reaches the ISCO and loses a little more angular momentum, it can no longer remain in orbit

Inside the ISCO, gas plunges rapidly into the black hole (so the density drops sharply)

- Most of the radiation it emits will fall with it into the black hole and is not observed
- Any energy, momentum and angular momentum it is carrying falls in with it

Bigl L12.20-21

Einstein's Gravity – General Relativity

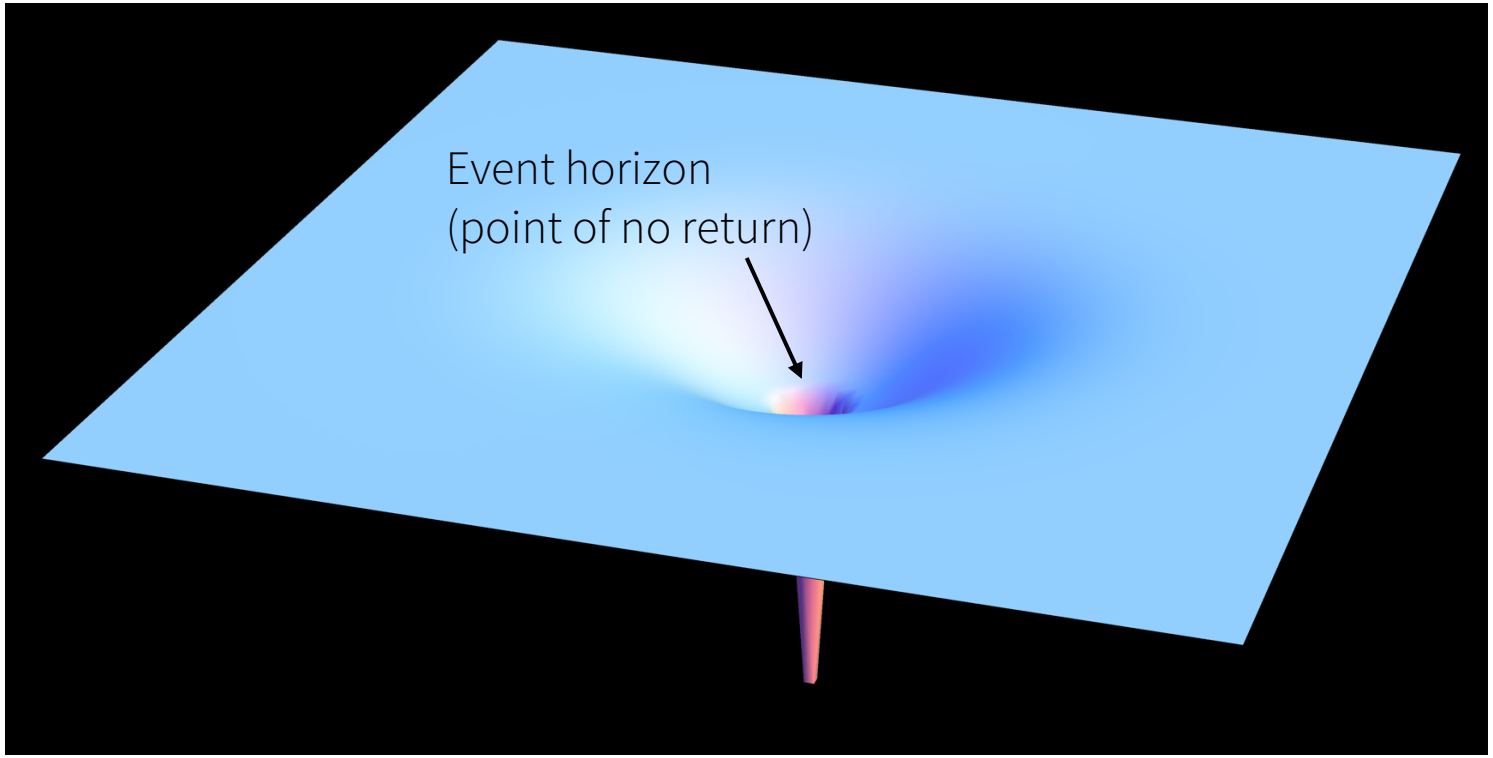


This is a curved 2D space. We can see the curvature when it's "embedded" in 3D. We live in curved 3D space (or 4D spacetime)

"Matter tells space how to curve. Space tells matter how to move" – John Archibald Wheeler

- Matter (and other stuff) causes curvature in spacetime
- Free particles obey Newton's First Law and move along geodesics (the shortest path between two points, equivalent of a straight line in flat space)
- Geodesics follow the curvature in space, for example towards a planet
- We experience this as the gravitational force

Black Holes in General Relativity

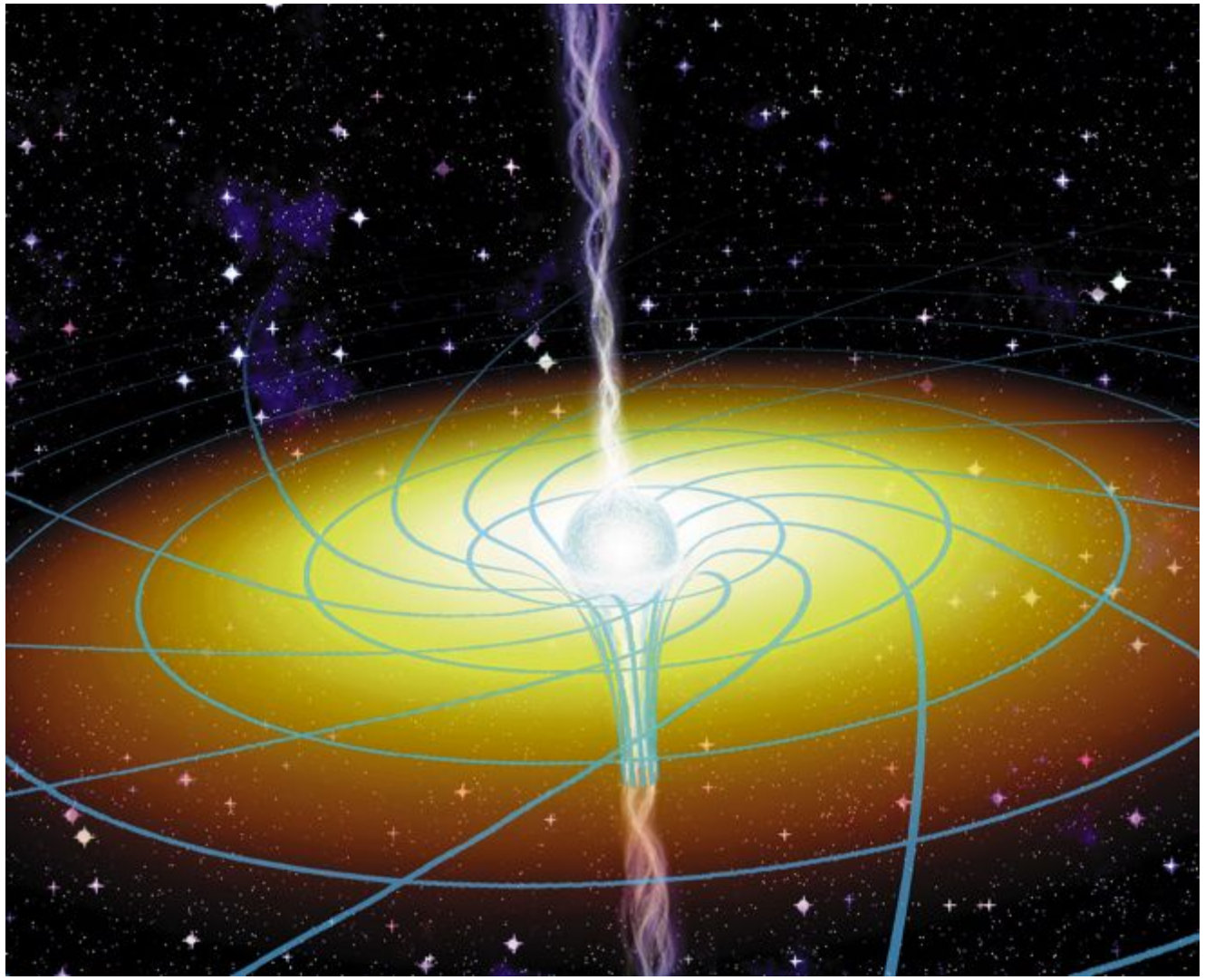


"Matter tells space how to curve. Space tells matter how to move" – John Archibald Wheeler

- Compact objects produce extreme spacetime curvature
- At large distances, the curvature is slight and the gravitational force is consistent with Newtonian gravity
- At the event horizon, curvature is strong
- All geodesics within the event horizon go towards the singularity — once inside the event horizon, the only way is inwards! WILtY

L13.11

Putting a spin on it!



When the central object (e.g. the black hole) is spinning, spacetime is 'dragged around with it' — frame dragging

WILtY

If you try to stand still, you will be pulled around in orbit (geodesics go around). To remain stationary, need to travel backwards

Rotation of space is faster at smaller radii

Inside the ergosphere around a spinning black hole, would need to travel backwards faster than the speed of light to remain stationary

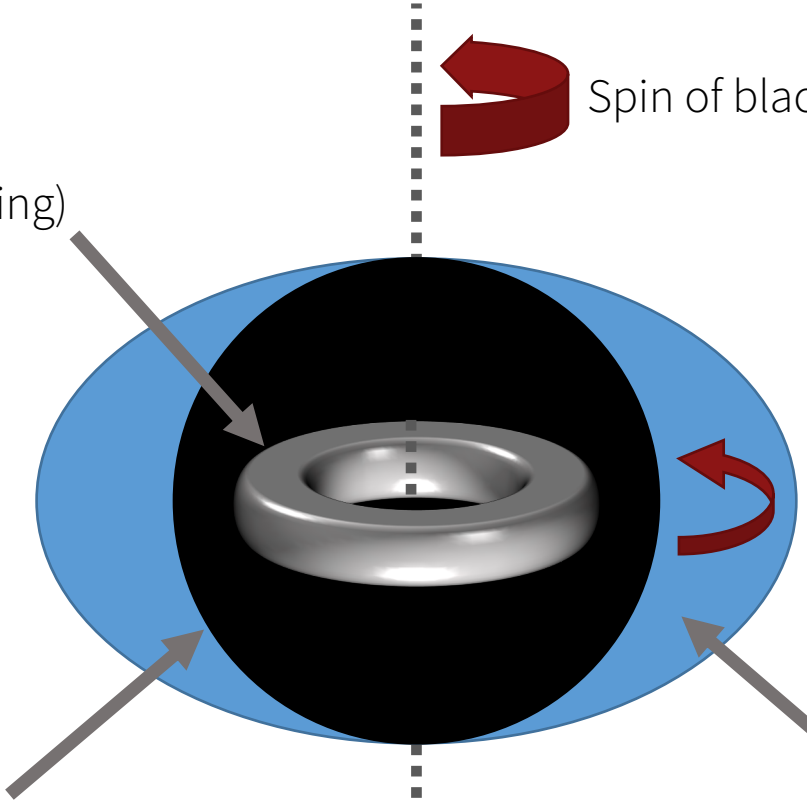
- Inside the ergosphere, it is impossible to remain stationary. Must orbit in the same direction as the black hole spin

Up to 29% of the mass of the black hole is in rotational energy and can be extracted

L13.12

TMI

Anatomy of a spinning black hole


Spin of black hole
Singularity (ring)
Event horizon
(smaller for more rapid spin)
• $r_H = 2\,{}^{GM}/_{c^2}$ when $a = 0$
• $r_H \sim {}^{GM}/_{c^2}$ when $a \sim 1$
Ergosphere
(must orbit in direction of black hole spin inside this region)
$r_E = 2\,{}^{GM}/_{c^2}$

The spin of the black hole is measured using the spin parameter, a, which is related to the angular momentum, $J = mrv$

$$a = \frac{J}{Mc}$$

The spin parameter is measured in units of ${}^{GM}/_{c^2}$ and can have a value from 0 to 1

- a = 1 is the maximum allowed spin. Above this value, the event horizon would spin faster than the speed of light, and the singularity would not be hidden behind the event horizon (violating the cosmic censorship conjecture)
- As the black hole spins up, the light that is emitted by the gas falling in tries to spin it down again, so astrophysical black holes likely reach a ~ 0.998

For a more rapidly spinning black hole, the event horizon is smaller

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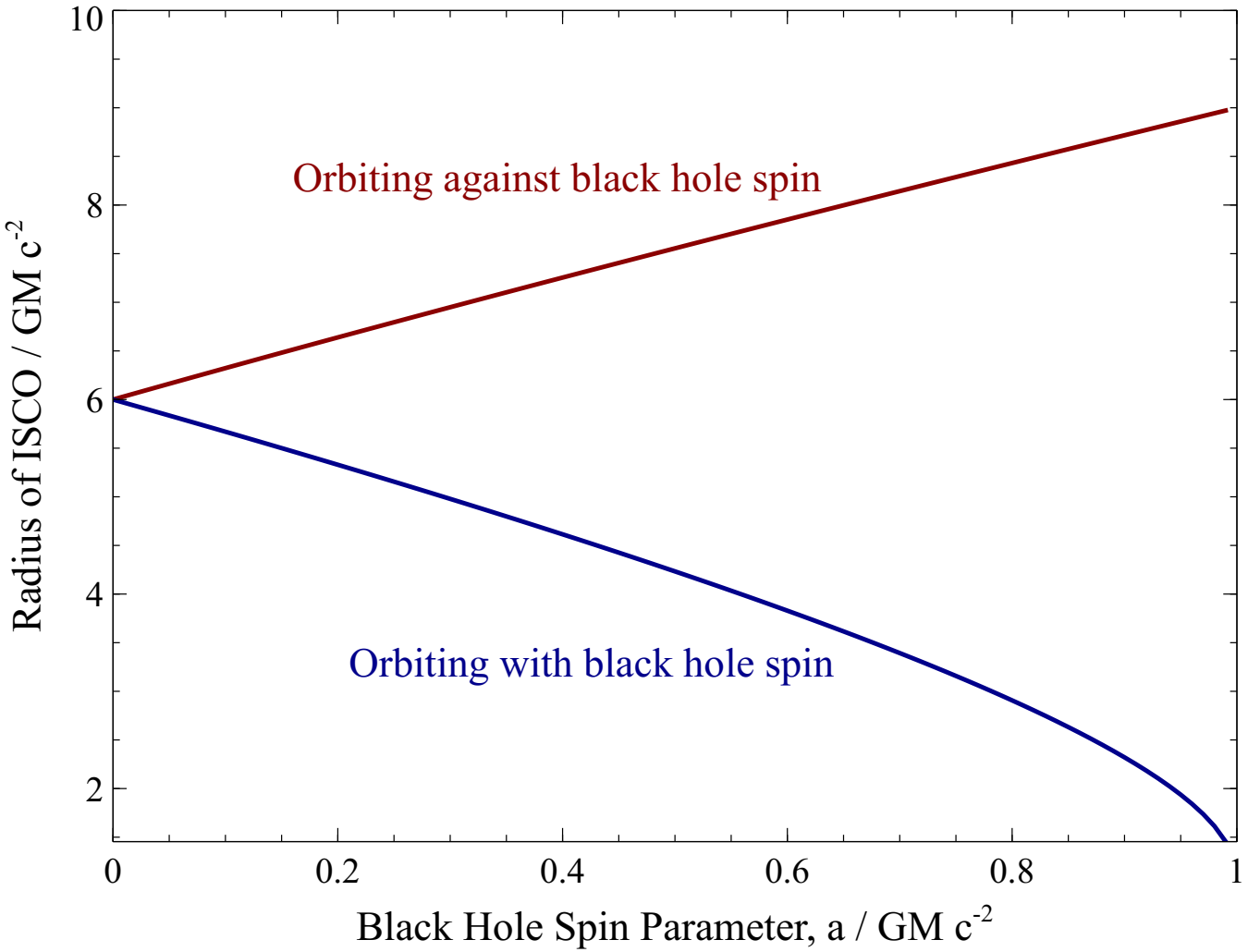
Orbiting a spinning black hole



If you are orbiting in the same direction as the spin of the black hole, the dragging of space underneath you helps you stay in orbit closer to the black hole

- For a non-spinning black hole, the innermost stable orbit, $r_{\mathrm{ISCO}} = 6\,{}^{GM}/_{c^2}$
- The faster the spin, the ISCO moves to smaller radii. For maximum spin, $r_{\mathrm{ISCO}} \sim 1\,{}^{GM}/_{c^2}$

If you are orbiting against the direction of the black hole spin, frame-dragging hinders your orbit and you must orbit further from the hole

- For maximum (opposite) spin, $r_{\mathrm{ISCO}} \sim 9\,{}^{GM}/_{c^2}$

Q1:

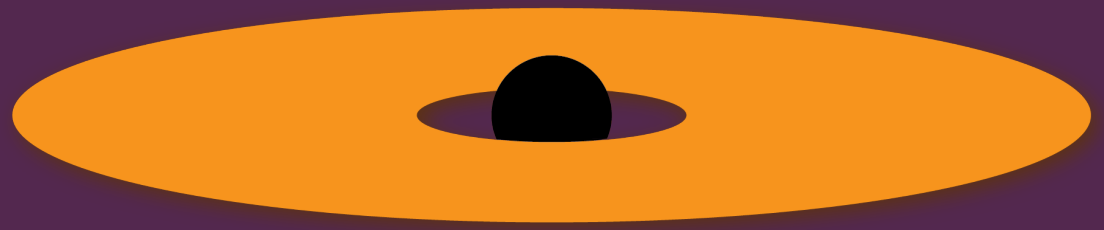
Consider a green flashlight in orbit around a non-spinning black hole at the innermost stable circular orbit (ISCO)

1. How will the color of the light appear to vary as it travels in its orbit?
2. If the black hole is spinning faster (and the flashlight is at the ISCO for the more rapidly spinning black hole), how will the colors seen compare to those seen around the non-spinning black hole?
3. Instead of a single flashlight, there is a continuous ring of green lights in orbit around the ISCO. We add up all the light we receive from the entire ring and measure the spectrum. How will this appear for the spinning and non-spinning black holes?

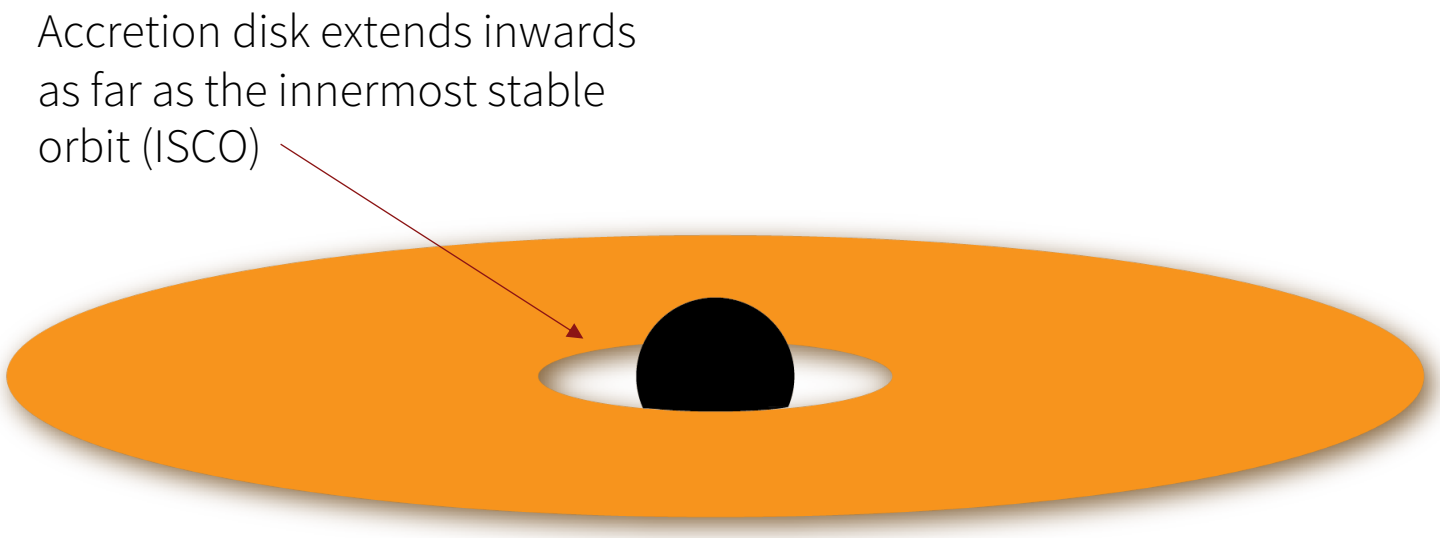
Q2:

How does the accretion disk around a non-spinning or slowly-spinning black hole differ from the accretion disk around a rapidly spinning black hole?

How will we be able to see the difference from the light that the accretion disk emits?



Accretion onto spinning black holes



As the spin of the black hole increases, the event horizon is smaller and the innermost stable orbit is closer to the black hole

The accretion disk extends to smaller radii around more rapidly spinning black holes

Gas only remains on stable circular orbits outside the innermost stable circular orbit (ISCO). Inside the ISCO, gas plunges rapidly into the black hole (so the density drops sharply and the disk essentially stops at the ISCO)

We see radiation emitted from gas in the disk before it reaches the ISCO (we don't see much emission from gas as it finaly plunges into the black hole)

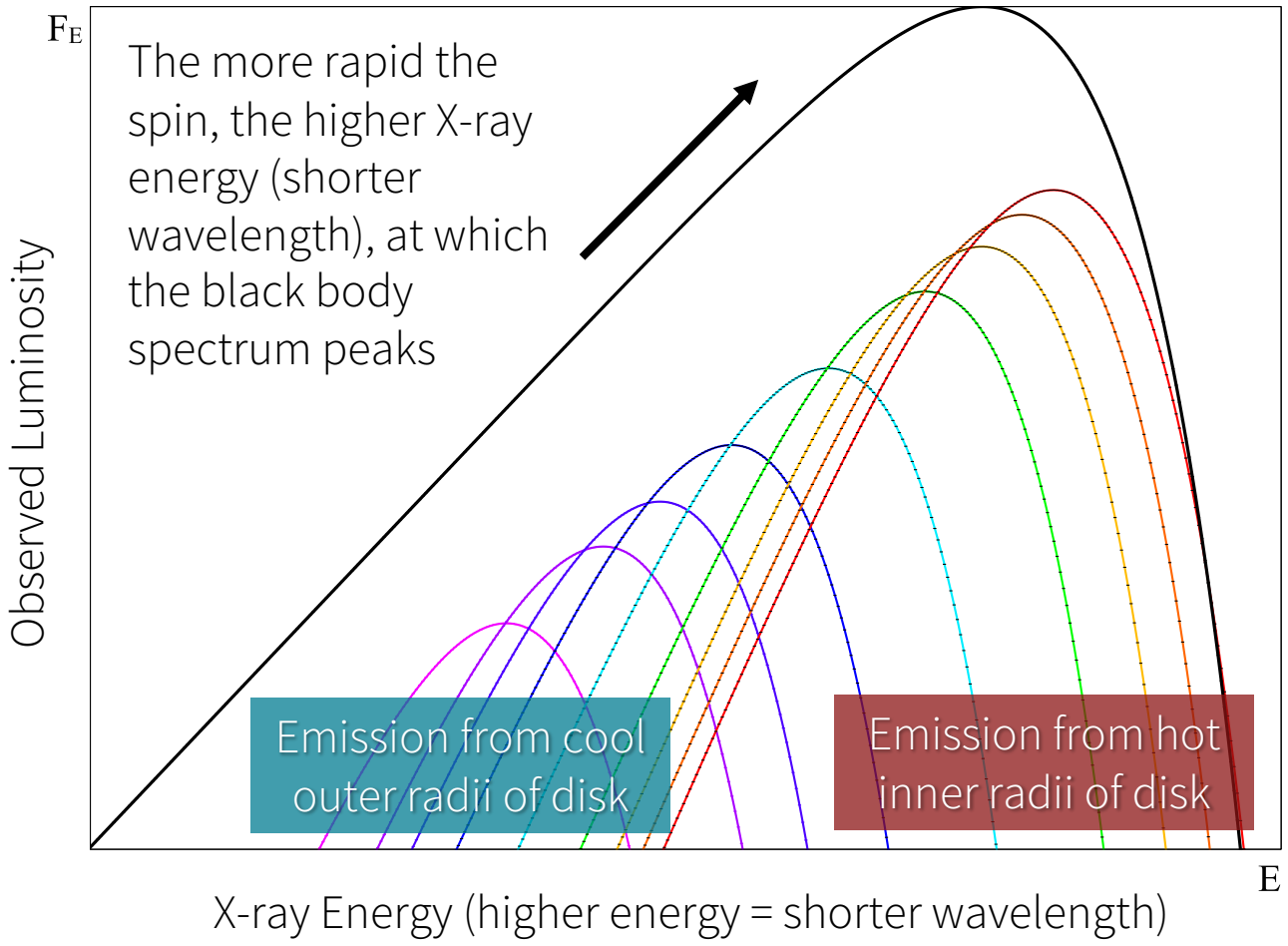
When the ISCO is closer to the black hole, more gravitational energy is released between the starting point of the gas at large radius and the ISCO (L7.16)

- ~6% mc^2 released when $a = 0$
- ~40% mc^2 released when $a \sim 1$

Rapidly spinning black holes can power a greater luminosity

Measuring the spin (1)

The spectrum measures how much light (X-rays) we see at different wavelengths (energies or colors)


F_E
The more rapid the spin, the higher X-ray energy (shorter wavelength), at which the black body spectrum peaks
Observed Luminosity
Emission from cool outer radii of disk
Emission from hot inner radii of disk
E
X-ray Energy (higher energy = shorter wavelength)

Gas in the accretion disk is heated by friction as it spirals towards the black hole

Gas at smaller radii is heated to higher temperatures

Accretion disk emits black body radiation (each radius emits according to the local temperature). Around a **stellar mass black hole**, this corresponds to **X-ray** wavelengths

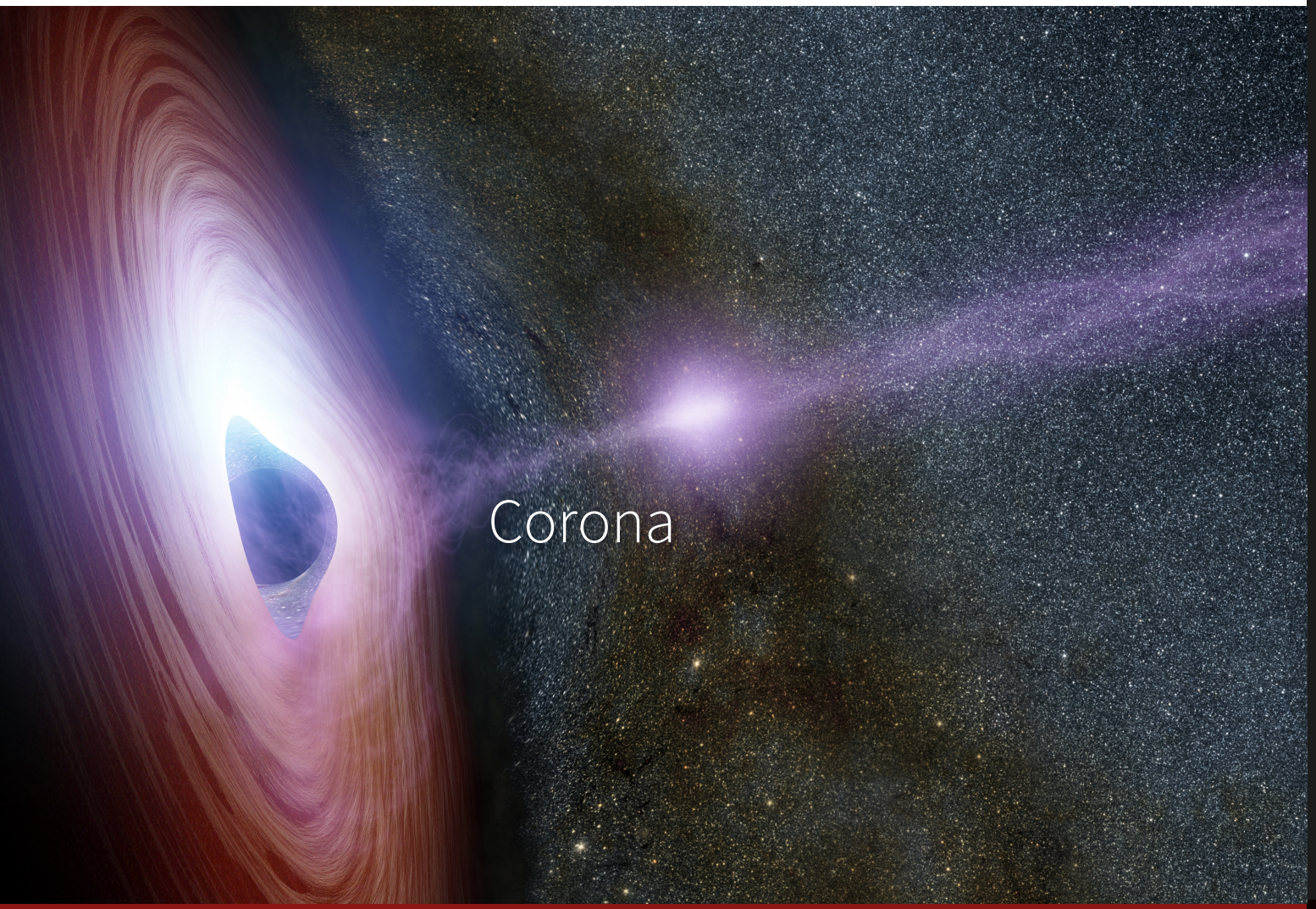
The total spectrum we measure is the sum of the spectrum from each radius

The higher the spin, the disk extends to smaller radius and reaches higher temperatures

We can measure the peak temperature of the inner accretion disk and use this to measure the spin of a stellar mass black hole

L7.15

Under the lamppost



WILtY

Accretion disk carries magnetic fields that get twisted up as the gas orbits the black hole L13.15

- accelerates electrons in a corona that produces an intense X-ray source

We observe some of the X-rays from the corona directly.

X-rays from the corona also shine down and illuminate the disk of gas that is falling into the black hole.

We can observe the accretion disk from the X-rays it reflects.

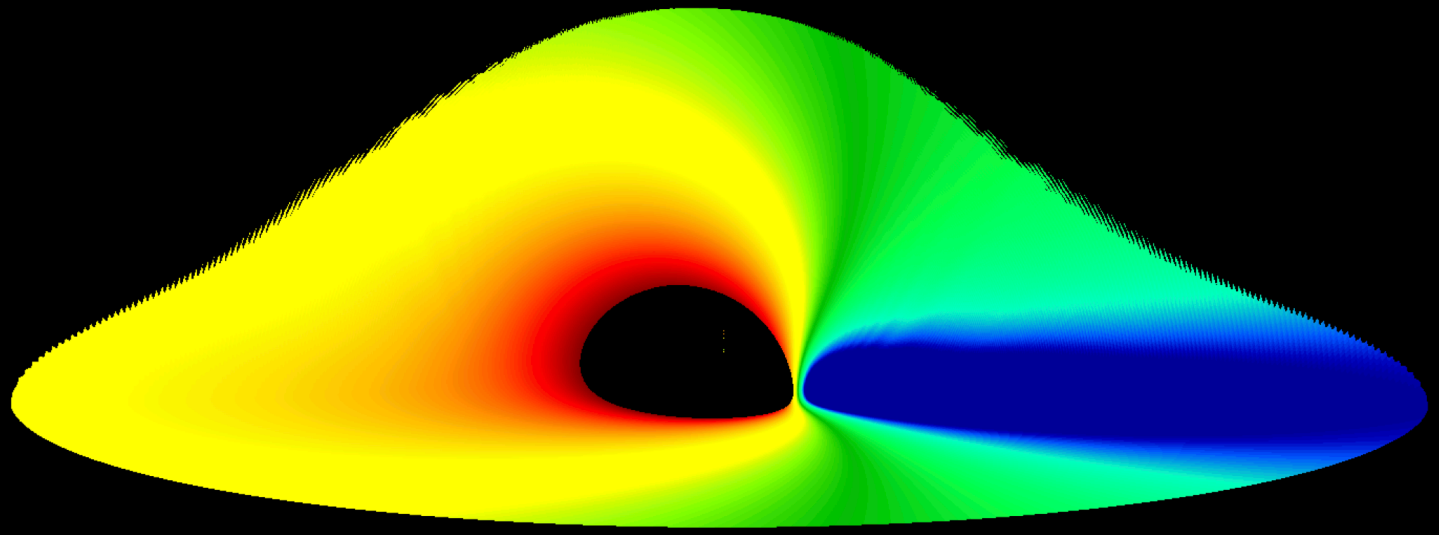
In particular, the X-rays cause atoms (particularly iron) in the disk to fluoresce. They absorb X-rays, then re-emit X-rays at specific energies (or wavelengths, or ‘colors’)

BigI | L5.25-26 | L6.16

More to come on imaging in L15

Reflection from the disk

X-rays emitted from close to the black hole undergo gravitational redshift as they climb out of the gravitational field (stronger close to the black hole)



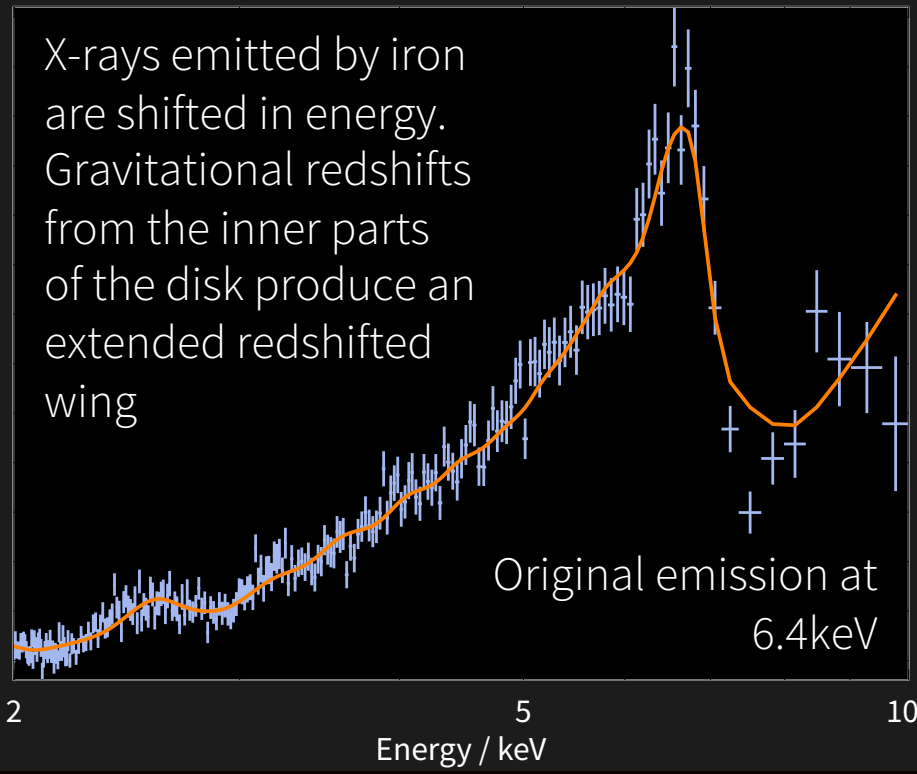
Doppler shifts due to orbital motion of disk. Approaching side is shifted to shorter wavelengths (bluer), receding side to longer wavelengths

Image of the observed color of (originally green) light from each part of disk

We cannot resolve an image of the disk. We see all the colors added together coming from a single point, but we can measure the spectrum

We observe the fluorescence from iron atoms in the accretion disk.

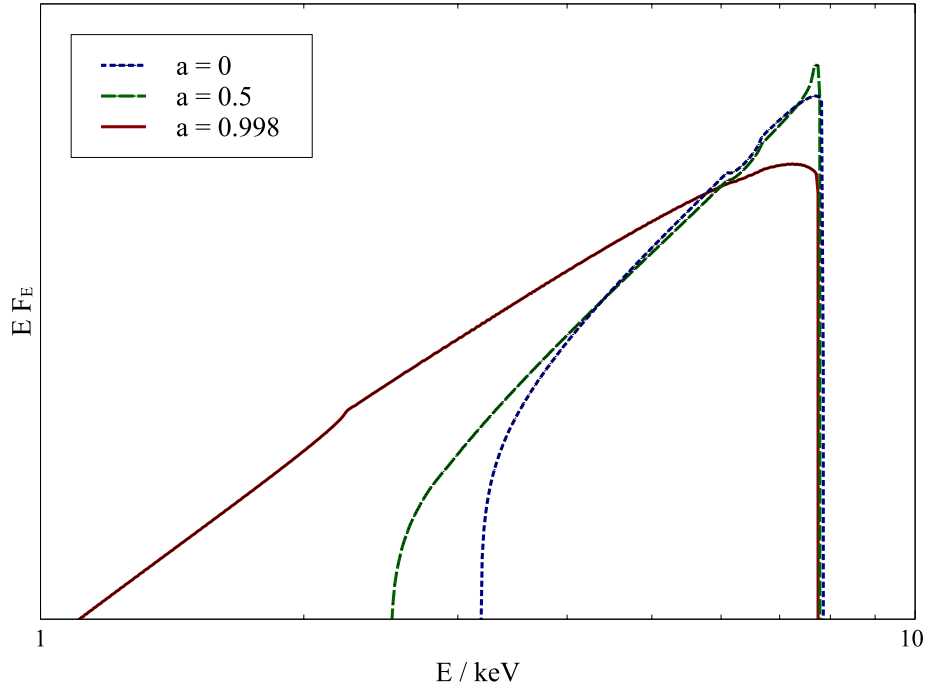
When illuminated by the X-rays from the corona, they emit X-rays at one specific energy (as observed in their own rest frame, orbiting close to the black hole)

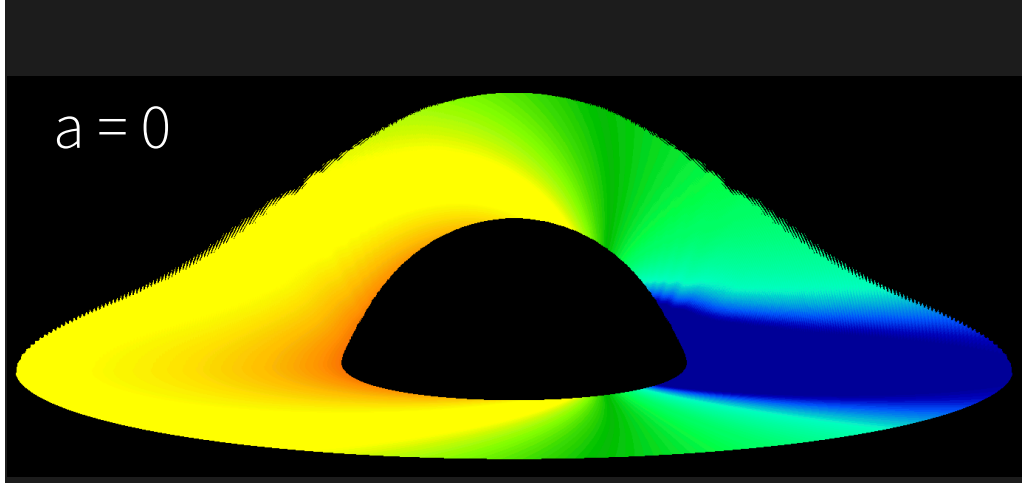

X-rays emitted by iron are shifted in energy. Gravitational redshifts from the inner parts of the disk produce an extended redshifted wing
Original emission at 6.4keV
2
5
10
Energy / keV

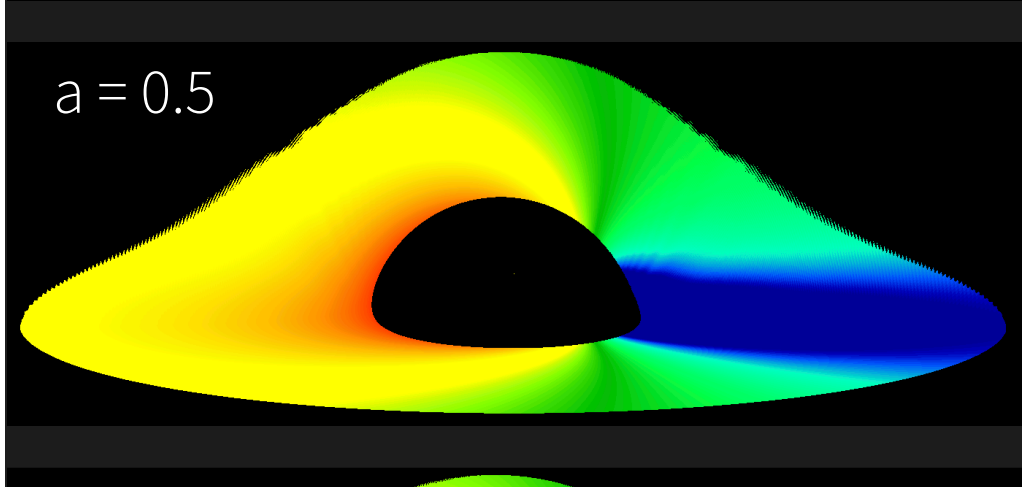
Measuring the spin (2)

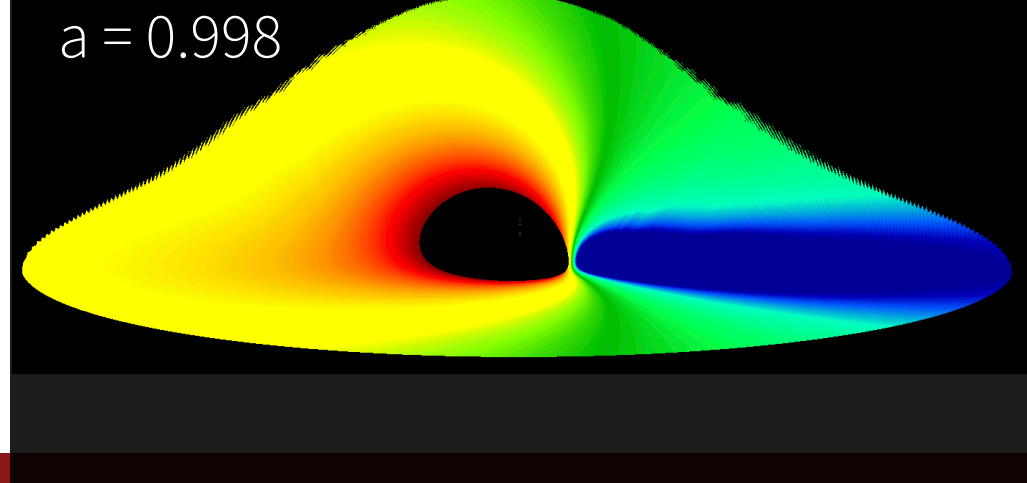
The more rapidly spinning the black hole, the closer to the black hole the accretion disk extends — the closer to the black hole, the stronger the gravitational redshift of X-rays emitted from atoms in the disk

By measuring the extent of the redshifted wing of the iron emission (the “line”) in the spectrum, can measure the spin of the black hole





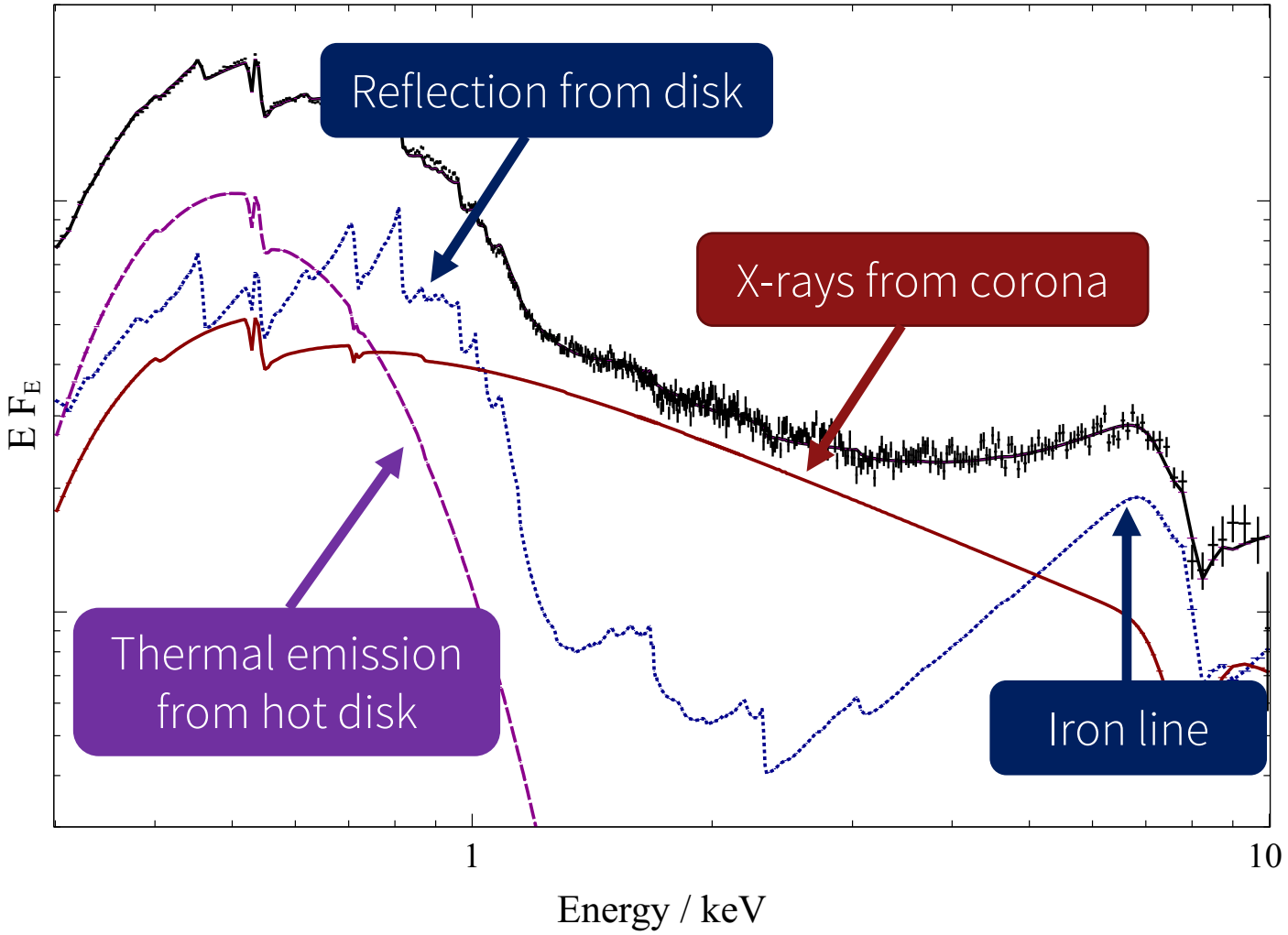




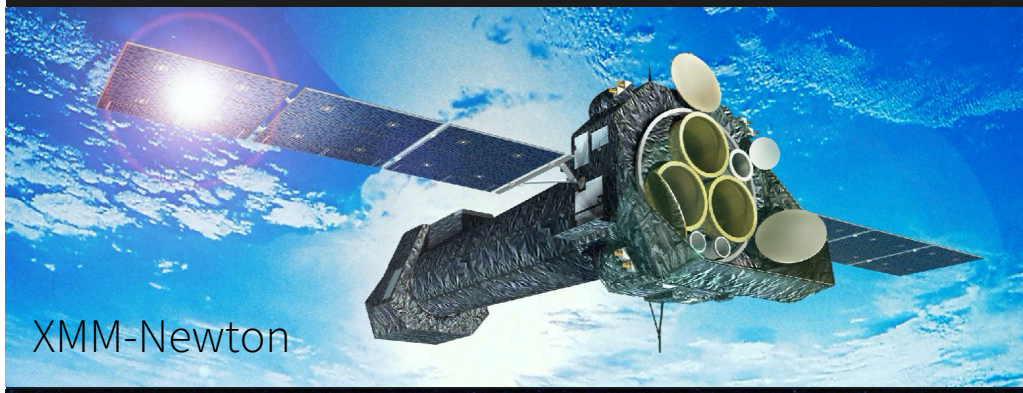
TMI

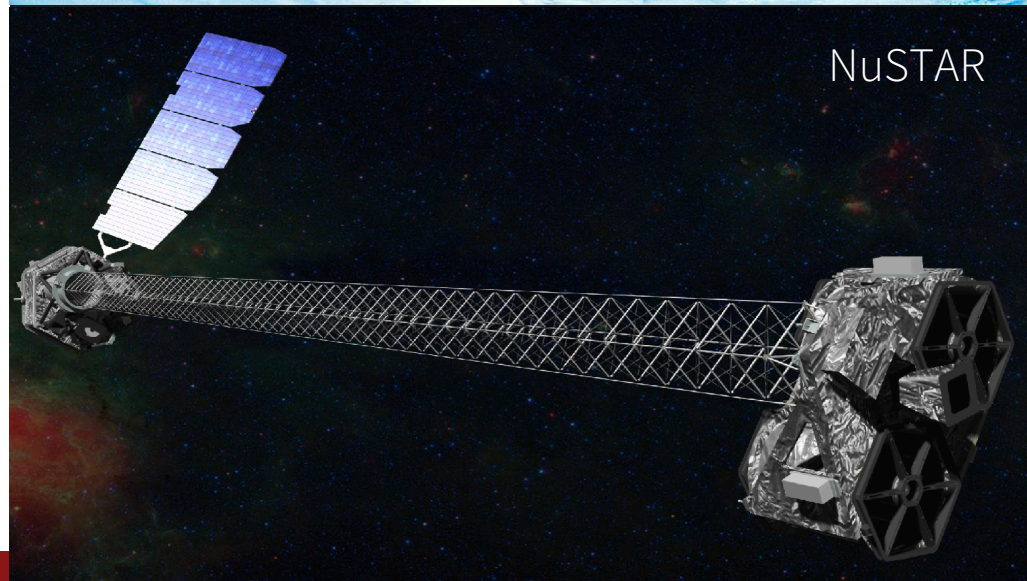
Observing black holes

X-ray spectrum of the AGN IRAS 13224-3809 from XMM-Newton

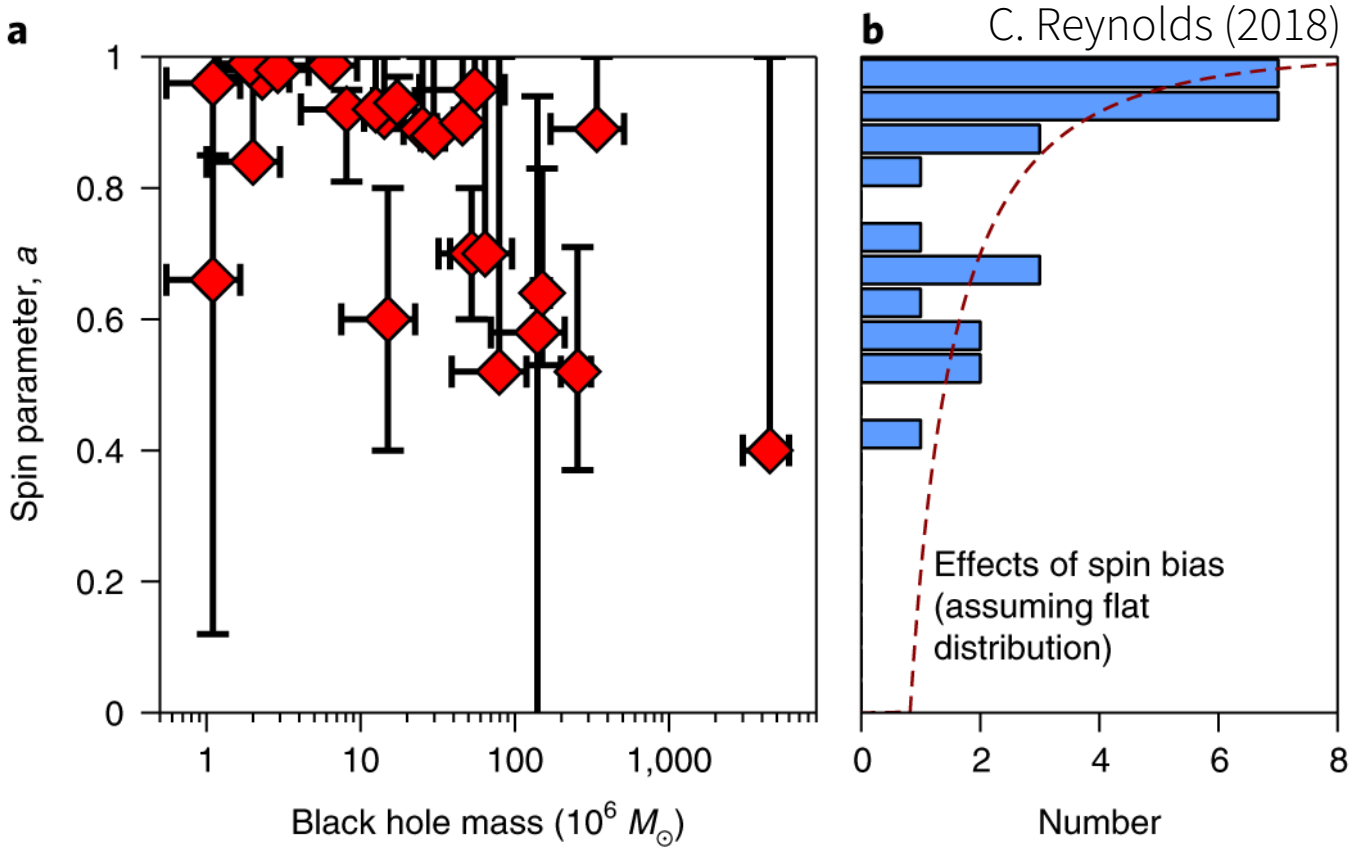


X-ray telescopes can't resolve the accretion disk (they appear as a single point of light), but can measure the energy of individual X-ray photons, so we can obtain the spectrum (number of photons at different energies)





Why do we care about the spin?



There's a catch! Spinning black holes power brighter light sources than non-spinning black holes, so of the black holes we can see from Earth, many will be spinning (a "selection effect")

As the black hole grows by accreting gas, angular momentum must be conserved

If a black hole grows by accreting gas spiraling in the same direction through an accretion disk, it will keep increasing the spin of the black hole

If the black hole grows by "chaotic accretion" with gas coming from different directions, sometimes it will spin up, sometimes it will spin down, so overall will end up with low spin

Measuring the spin of a sample of many black holes across the Universe tells us how they grew

Bigl

- Frame dragging around spinning black holes
- Innermost stable orbit
- The more rapid the black hole spin, the smaller the event horizon and the closer the innermost stable orbit
- Can measure the spin of a black hole by observing how close to the black hole the the accretion disk extends — temperature or gravitational redshift of X-rays emitted form the disk
- Measuring the spin of many black holes tells us how they grow